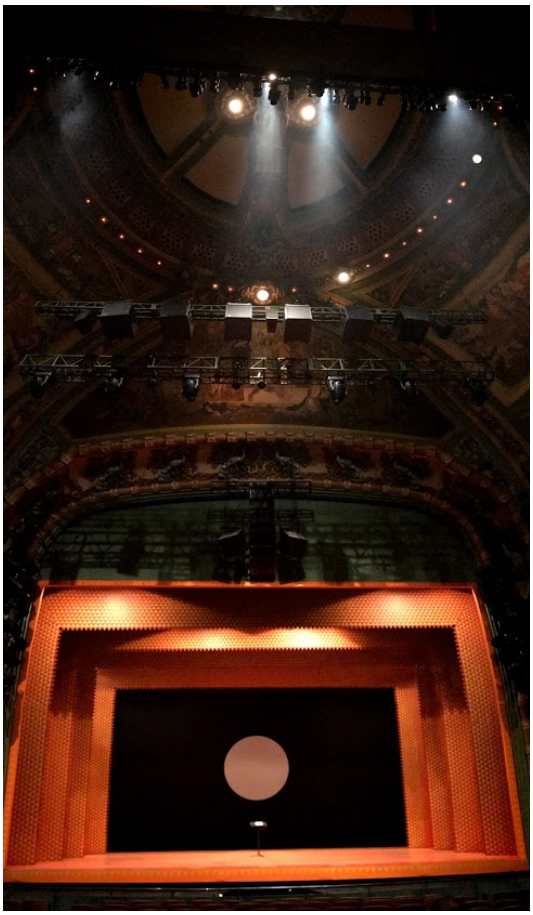
CASE STUDY

DISTRIBUTION AND CONTROL OF GRIGNARD PURE™

AT THE NEW AMSTERDAM THEATRE

JANUARY 2021

SUMMARY CONCLUSION



Through injection into a building's traditional HVAC system, Grignard Pure's (GP) microdroplet aerosolized airborne antimicrobial can be delivered effectively and expediently to all occupied spaces served by that HVAC system. In controlled testing at the New Amsterdam Theatre, it was demonstrated that in an aerosolized microdroplet state (hereafter referred to as "air treatment"), GP behaves like a gas in its ability to distribute, dilute, and disperse in the atmosphere of occupied spaces. In real time, the concentration of GP in the occupied spaces could be reliably measured, and the GP production levels from the atomizer, through the use of closed-loop feedback control systems, could be consistently and reliably controlled and monitored.

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In late January of 2020, the first reported cases of severe acute respiratory syndrome coronavirus 2 (COVID-19) were confirmed in the United States.[1] By the middle of March, New York State was overwhelmed by the effects of the virus and was left in a state of emergency trying to provide sufficient medical care to those afflicted by the virus. In response to the dire conditions it was facing, New York State issued an order on March 20 to close all businesses that were deemed non-essential.[2] It was quickly determined that indoor spaces presented an increased risk to transmitting the virus, particularly spaces that would be densely occupied. Despite identifying some modifications to existing building heating, ventilation, and air conditioning (HVAC) systems, such as increasing the percentage of outdoor air to the occupied spaces and increasing filter efficiency at the HVAC equipment, no combination of measures has, to date, proven sufficient to safely reopen tightly packed indoor spaces such as live performance theaters, concert venues, and sporting events.

In early June, a team of engineers, scientists, and theater professionals was assembled by Disney Theatrical Productions and tasked with developing a strategy for reopening these types of spaces. The team was comprised of engineers from Jaros, Baum & Bolles, scientists from Grignard Pure (GP) and The Ambient Group, special effects designers from JFMX, and building engineers from Penguin Mechanical. The team's design solution centered around the deployment of Grignard Pure, an innovative 'airborne antimicrobial' that, when introduced to the COVID-19 virus in the air, can inactivate more than 98% of the virus in less than one minute, as reported by an internationally recognized lab. GP forms small microdroplets that float in the air and condense on virus particles, quickly inactivating the virus and, as such, significantly reducing the primary cause of infection.[3] Having identified an aerosolized disinfectant as a promising solution, two design challenges faced the team: how to effectively introduce the GP microdroplets into occupied spaces; and how to measure the concentration of GP in the occupied spaces and control microdroplet production. The design team set out to start addressing these questions.

While the application of GP as an airborne antimicrobial was the novel idea the design team was investigating, GP has been used for more than 20 years as a theatrical lighting effect under a different label in Broadway shows and live music productions. GP is generated through standard special effect atomizer machines in large plumes of rolling haze (Figure 1).

Figure 1: Grignard Pure distributed by a standard theatrical atomizer.

The first decision the design team needed to make was whether the GP would primarily be delivered from a centralized hazing unit location or introduced locally into each occupied zone. Two factors led the design team toward a centralized unit location solution. The first consideration was the perceived experience of people inside the occupied zone. As a airborne antimicrobial, GP is effective at concentrations at or below the visible level. However, the atomizer machines that generate the GP microdroplets are designed to intentionally create visible smoke for stage and lighting effects. This was a concern, as it could be construed by the occupants as intrusive and unsettling to be in a space seeing the atomizer machine pump out "smoke". In addition, large concentrations of haze were determined to increase the risk of triggering local (optical) fire alarm area smoke detectors. With one unit serving multiple spaces through the HVAC systems, the air treatment-generating machine can be located farther away from the spaces it serves, which allows the microdroplets time to partially evaporate, mix and disperse within the larger airstream. The second consideration that drove the design team to prefer a central dispersion unit was from an operational perspective. These dispersion units have reservoirs that hold liquid GP. As the unit operates, a small pump injects the liquid GP onto a heating element to create the microdroplet air treatment. Periodically, these reservoirs need to be refilled with liquid GP. To have small atomizers in every local space would require building management to constantly service these units and disrupt the occupied spaces. Having settled on a central dispersion unit configuration, the question was then how to implement one dispersion unit to serve multiple spaces. The answer lies in a building's existing HVAC system.

Utilizing an existing HVAC system to deliver the GP microdroplets to multiple spaces quickly became the agreed-upon design strategy. This also allowed the design team to leverage established principles of airflow distribution to help dilute and disperse the microdroplets throughout the occupied space. Distributing and dispersing the microdroplets would both increase the effective area covered while mitigating any points of high or low concentration. Assuming

that the GP microdroplets behaved like a gas in the airstream, the law of partial pressures states that while in the volume of an occupied space, the total pressure of the mixture of normal room air and microdroplets will be the sum of each individual part. This means that the law of partial pressures characterizes good mixing of the GP microdroplets and the room air over time. Another guiding HVAC air distribution principle known as the Coandă effect promotes room air entrainment and space mixing. As the microdroplets come out of the HVAC supply register, the microdroplet latent air will cling to the ceiling and gradually fall into the space, creating good mixing inside the space (Figure 2).

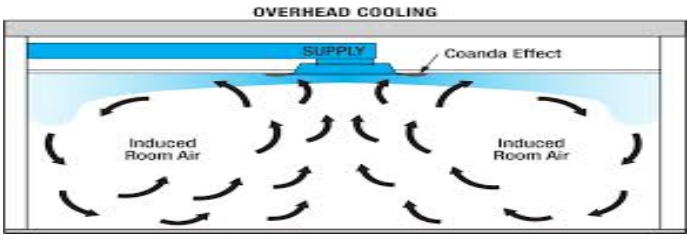

Figure 2: Coandă effect promotes good space mixing of GP microdroplets with the induced room air.[4]

The simplest method for introducing the air treatment into the HVAC system was simply to place the dispersion unit inside the discharge plenum of an air handling unit (AHU) and letting the dispersion unit introduce the microdroplets directly into the supply airstream. However, it was quickly recognized that all large building AHUs are required by code to have a duct-mounted smoke detector (DSD) installed in the supply air ductwork just outside the discharge of the AHU. This DSD is tied to the building fire alarm system and will shut down the AHU and send an alarm to the building engineers if its sensors are tripped. Given that the microdroplets are generated in a thick haze, locating the dispersion unit upstream of the DSD would invariably trip the sensors and create an alarm. The design team now zeroed in on areas in the supply ductwork, downstream of the DSD.

Introducing the GP microdroplets into the supply air ductwork had its own set of challenges. The first requirement was that the GP microdroplets need to be injected into the airstream upstream of any taps off the main discharge duct. If tapped downstream of a tap, that space would not receive any GP microdroplets in their supply air. Through the use of Computational Fluid Dynamic (CFD) analysis, the team determined that a straight run of approximately 6 feet from the injection point of the microdroplets to the first duct tap was required, so that the microdroplets had some opportunity to mix with the complete volume of the primary supply air stream. Additionally, there were some complications regarding how the microdroplets would reach the primary supply airstream. The dispersion units that

generate the microdroplets have a small fan that blows out the air treatment. This fan has effectively no available external static pressure, so it cannot overcome the routine pressures commonly found in the vast majority of HVAC supply air systems. This led to two HVAC design strategies. The first would rely on a side stream of supply air being tapped upstream of the intended injection point and ducted to the inlet of the hazing machine. The dispersion unit discharge is then ducted back into the supply airstream, essentially allowing the primary supply airstream to blow through the dispersion unit (Figure 3). The second design strategy would rely on the premise of cowl induction, in which the high velocity of the primary supply airstream would create an area of low pressure around the air treatment induction point and draw the GP into the supply airstream (Figure 4). The dispersion unit manufacturer advised on the maximum flow rate at the discharge of the microdroplets, so cubic feet per minute (cfm) and static pressure could be considered when modeling these design solutions. With a plan in place for how to introduce the microdroplets into the occupied spaces, the team turned its focus to the question of how to control the concentration levels in the space.

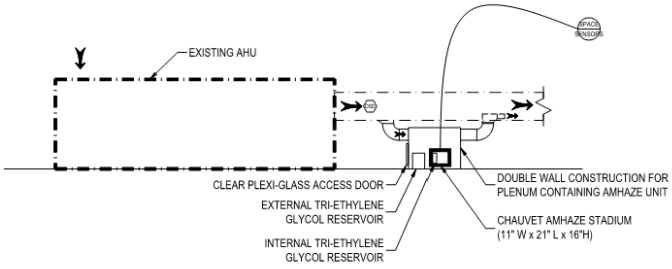

Figure 3 – Sidestream configuration allows the supply air to blow through the hazing machine.

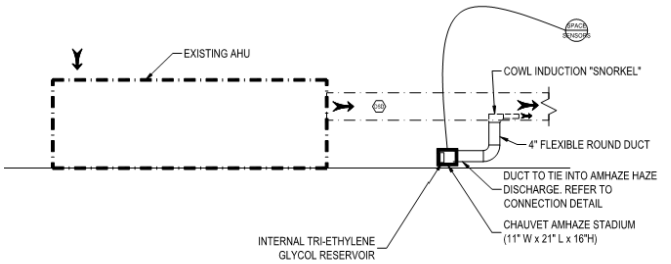

Figure 4 – Cowl induction configuration induces the air treatment into the supply airstream.

Controlling the level of microdroplet concentration in the occupied spaces requires two different components. The first control component has to do with the sensors and control systems that monitor the concentration of GP microdroplets in the occupied spaces. The team was able to develop a wireless, mesh system of sensor control units (SCUs) that were placed in various locations throughout the occupied zones as part of the Pure system management. The SCUs have particle mass sensors that detect four different sizes of

particles: 0.3 to 1.0 µm, 0.3 to 2.5 µm , 0.3 to 4.0 µm , 0.3 to 10.0 µm , with an accuracy of +-10% The sensor will record a total particle count in the measured space. The SCU utilizes a particle sensor. Based on the particle size and particle count, a mass concentration of GP (mg/m^3) can be calculated and reported back to the Pure logic controllers. Each of these SCUs was then paired to a sensor management unit (SMU) that was located on the hazing unit. The SMU uses all the data provided by the array of SCUs to control the atomizer operation (fluid pump and dispersion fan). All the SCUs communicate over mesh WiFi, and the SMU interfaces with the dispersion unit through a DMX cable (standard theatrical control cabling for stage equipment). All control devices were 5V or 12V units, powered with a battery pack plugged into a 120V receptacle. The recorded mass density became the basis for establishing readable levels within the occupied spaces and target set points for dispersion unit control. Local current-sensing elements were also connected between the SMU and the air handling unit fan systems, so that the atomizer machine could not operate if the air handling unit fan system was not operating.

The second component to controllability has to do with the dispersion unit that generates the GP microdroplets. To this point, the dispersion machines have been assumed to be any standard theatrical hazing machine unit. When evaluating the hazing machines, two factors proved paramount in selecting the right equipment. The first factor was the ability to control the microdroplet discharge from the machine. Most hazing machines have step-function discharge ranges (low, medium, high). These coarse scale adjustments do not bode well for precision space concentration control, so looking for a hazing machine that had proportional control became a key requirement. The second factor in selecting a dispersion unit was its ability to communicate with the sensors in the occupied spaces. The team would need a atomizer machine that could accept input from the sensor control logic and respond accordingly. Ultimately, the team decided to proceed with the Amhaze Stadium unit, manufactured by Chauvet. The unit has proportional control on both the GP liquid pump and the discharge fan, allowing for improved responsiveness when compared to other units, and the unit was readily adaptable to receive input from the Pure control network. With the HVAC design in place and the controls schemes established, it was time for theory to meet practice. After discussions with Disney Theatrical Productions, the New Amsterdam Theatre on Broadway was selected for a two-week proof of concept testing locations.

After identifying the test site location, the process of creating a site-specific action plan began. The design team walked the site to review the building's existing HVAC infrastructure and reviewed building design documents to identify the primary areas of focus for the study. The areas of focus were identified as the main seating auditorium, multiple levels of balcony seating, the stage, stage support areas under the stage, the orchestra pit, and various general areas of congregation. These spaces were served by five air handling systems: AC-1, AC-2, AC-3, AC-4 and AC-5. Once these areas were identified, the engineering team zoned these areas out based on the air handling unit serving the space and located SCUs for occupied space readings. SCU locations were reviewed by the design team for areas of high people concentration, patterns of airflow throughout the space, and areas of low airflow or 'dead zones' (Figure 5). The induction points from the dispersion unit into the primary supply airstreams were coordinated and reviewed with the building's operating engineers. Several testing issues quickly became apparent. The HVAC system was largely low-velocity, low-pressure ductwork, with minimal opportunities to access the ductwork. The low-velocity ductwork would dramatically reduce the effectiveness of the cowl induction detail, and limited access points meant that the team needed to compromise on points of poorer mechanical performance for ease of installation. Also, a large ceiling height in the main auditorium area created one large volume, with only supply air distribution from a single source at the top of the room. This would create a tough condition to monitor, with sensors at various locations and heights, and attempt to control.

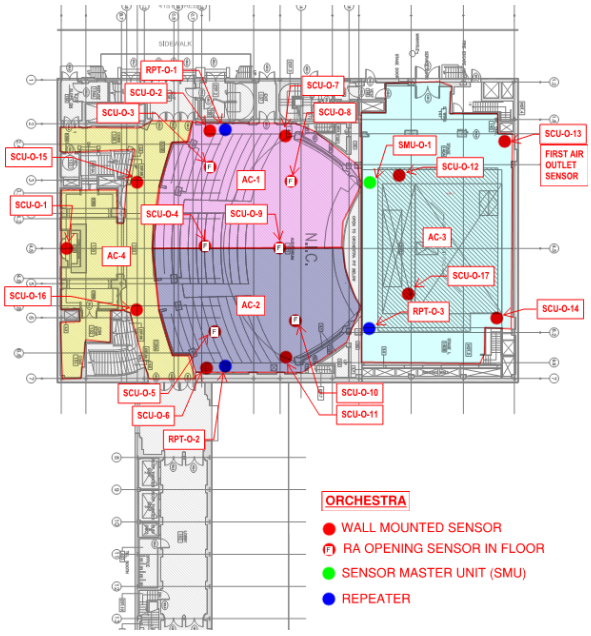

Figure 5 – AHU zoning and SCU locations for orchestra seating area.

Once initial loadout commenced in the theater, there was mixed success with the mechanical induction of microdroplets into the supply airstream. The cowl induction strategy relies on high velocities to create an

induced suction static pressure that exceeds the positive static pressure of the supply air duct. Given the low velocity of the supply air, effective cowl induction could not be achieved (Figure 6). For some air handling units, this was remedied by implementing the sidestream configuration for introducing air treatment into the airstream. For other units, there was not sufficient duct run to have both a tap upstream and downstream of the atomizer. For these units, the entire hazing machine was placed inside duct plenums so that testing could be conducted in the occupied spaces.

Figure 6 – Cowl Induction configuration could not achieve required static for induced flow in low velocity ductwork.

Once all the dispersion unit locations were finalized in the field at the end of the second day of the installation, all spaces on each HVAC system were able to be visibly confirmed to be carrying GP microdroplets at a high concentration (Figure 7 and Figure 8). The large air volume of the main auditorium had an effective air change rate of 4 air changes per hour. This resulted in changes of the air treatment concentration in the space taking approximately 20 to 30 minutes to evenly disperse in the space once a change in air treatment unit output was implemented. While observing the high concentration of visible GP microdroplets in the space, it was worth noting that once at a visible level, the GP would evaporate from the space in a noticeably quick time period of 15 - 20 minutes once air treatment production was stopped.

Figure 7 – GP microdroplets can be seen faintly in supply ductwork just downstream of GP injection point.

Figure 8 – Lights refracting in the Grignard Pure microdroplets in the main auditorium during testing.

With all the dispersion units properly introducing microdroplets in the supply airstream, the focus of testing shifted toward the controls. Initially, the dispersion units' output was manually controlled by the special effects team, and the Pure SCUs were recording and data-logging the total particle concentration and interpolating a respective mass concentration of GP in the measured zone. Atomizer outputs of 20% and 30% would commonly result in readings of 0.3 to 1.0 mg/m^3. Thirty percent unit discharge limit proved to be more than enough microdroplet air treatment in any one system. The units could produce significantly more product output than was required. The SCUs were then calibrated and properly zoned to the respective SMU.

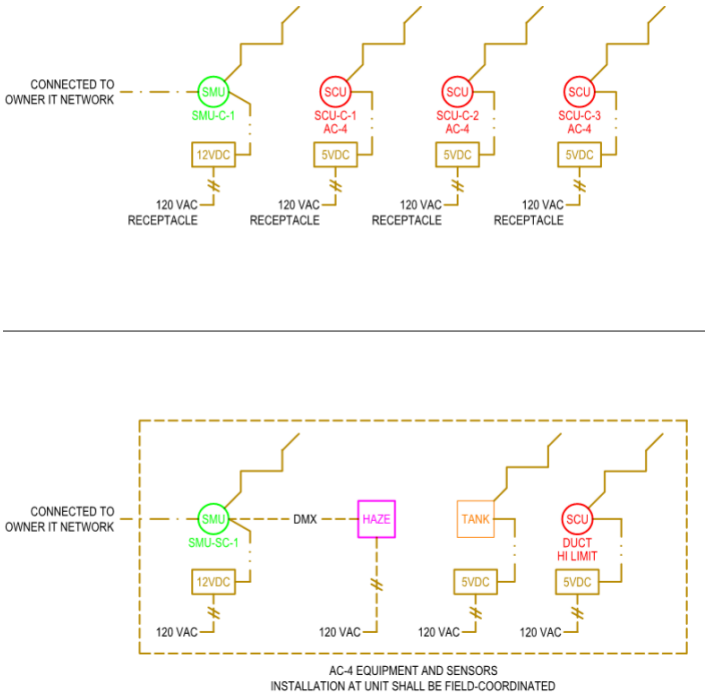

Figure 9 – Pure SCU's, SMU's, and other network devices control diagram for NAT)

Once a zone's SCUs were all calibrated and zoned, a zone average value could be interpolated from the various sensors. After several days, atomizer control switched from manual manipulation by the FX team to control through the Pure system . A target mass concentration range could be input, and the system would modulate discharge from the atomizer to maintain the average concentration in the space at that level (Figure 10). All sensors in a zone were reporting levels of GP concentrations within a limited range around the total zone average.

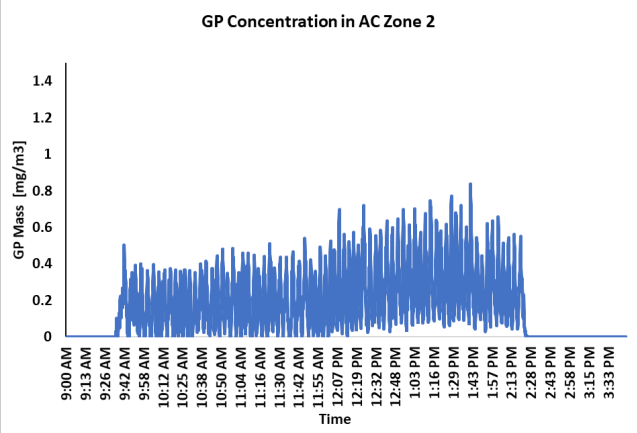

Figure 10 – Pure SCU's record real time mass concentration and process data to control GP output)

During various days of testing, target test range values varied from 0.3 mg/m^3 to 2.5 mg/m^3. It was established by the GP team that a mass concentration of 1.66 mg/m^3 over a time-weighted average was the required benchmark for virus inactivation per the EPA testing (note this value may be lowered from the time of this publication). This concentration bordered on the slightly visible spectrum within the occupied spaces.

While the Pure sensors were recording the total particle concentration and calculating and controlling the GP concentration in the occupied zones, several other teams were recording the actual mass concentrations of GP on their own sensors at the same time. In post experiment data processing, the Pure SCU sensor readings were validated against these recordings from the Ambient Group's high-acuity TSI sensor and Grignard Pure's PDR sensor. When comparing a plot of the GP mass concentration as measured by the TSI sensor to the total particle concentration as measured by the SCU sensor, it is evident that the two sensors tracked the same proportional changes in levels over the same period of time This means that in real time, the SCU sensors were detecting the same proportional change in GP concentrations based on the changes in the measured total particle concentration (Figure 11).

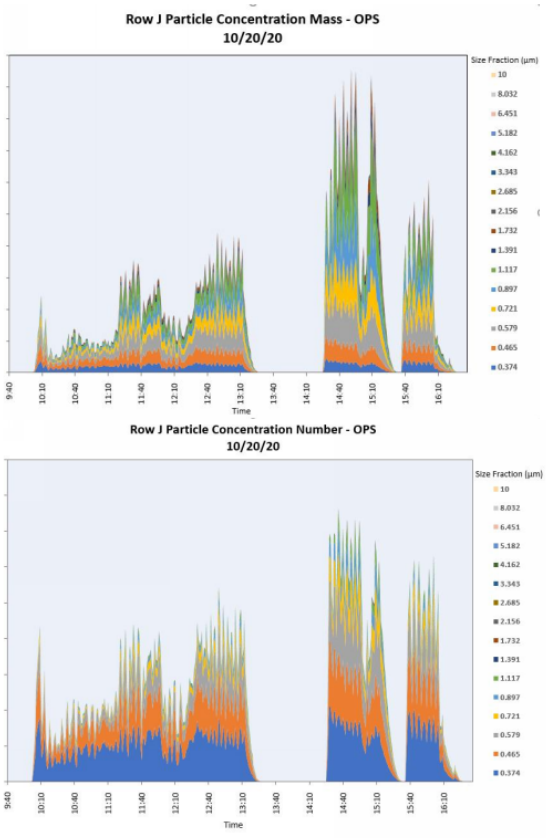

Figure 11 – On a normalized Y axis, the top graph is the actual GP mass concentration recorded on the TSI sensor. The bottom graph reflects the total particle concentration measured on the SCU sensor.

During testing, a close approximate conversion from total particle count to GP mass concentration was used by the Pure software. A post experiment effort between the Ambient Group and Grignard Pure resulted in an extremely strong correlation between the GP mass concentration measured by the TSI and the total particle concentration measured by the SCU's (Figure 12) This means that with great certainty, the Pure SCU's can accurately report the microdroplet concentration of GP in the measured zone. With real-time tracking verified and a strong correlation between total particle count measured by the SCU's and the total GP mass concentration in the air, it can be reasonably accepted that the Pure SCU's can accurately, consistently, and reliably control the GP mass concentration in occupied zones in real time.

During the two-week testing period at the New Amsterdam Theatre, the team was sufficiently able to validate that GP microdroplets can effectively be distributed by a building's existing HVAC system. The Pure system management was able to record the GP microdroplet concentration in various occupied test zones and modulate the output at the hazing machine to maintain a target space concentration level. One unexpected outcome of the test was that the GP microdroplets did not evaporate immediately

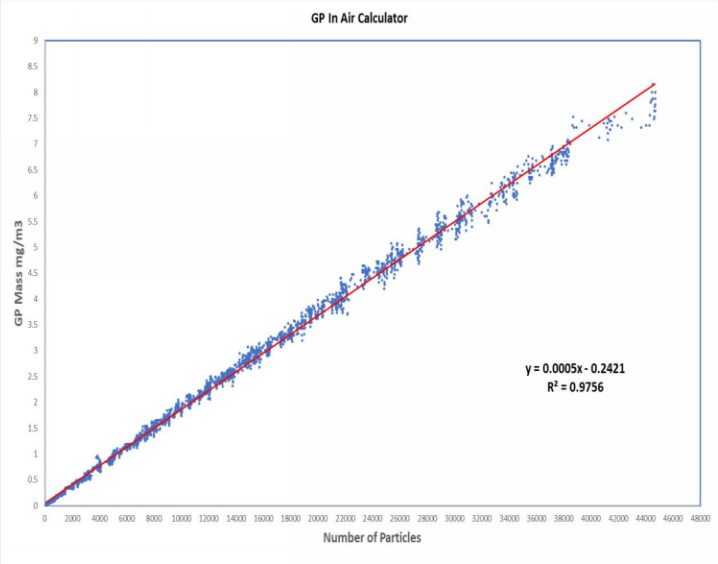

Figure 12 – A plot of total particles (X-axis) and measured GP mass concentration (Y-axis) shows a very strong correlation, with a coefficient of determination of 0.9756.

when introduced into the supply air or occupied spaces. There consistently remained a slight visual air treatment in the occupied spaces at most target concentrations. This may partially be attributed to the lighting in the space. Further evaluation would be required. The GP microdroplets lingered in the air for enough time that the return air filters back at the air handling unit were noticeably damp with GP moisture. This actually is a good thing from a viral protection perspective, as the damp filters are coated with GP and are therefore inactivating the virus in both the occupied space and again in the return airstream. The building engineers confirmed that after a few hours of not running the atomizers, the dampness

evaporated from the filters, with no damage to the filter itself.

While the test exceeded our expectations for testing at a large scale, the team has identified several areas of improvement for future installations. The first improvement pertains to the atomizers proper. As previously stated, these units have a tremendous capacity for generating microdroplet output, as they are designed for producing as much haze as possible for theatrical and other entertainment events. A refinement of the unit's capacity control, specifically to be more proportionally controllable to the required mass concentration, would be a significant improvement for controlling air treatment visibility as well as finer control over microdroplet concentration. Another modification to the atomizers would be to include a higher static pressure discharge fan. Having a more robust fan would help to resolve some limiting factors associated as to where microdroplets can be introduced into the primary HVAC system supply air stream.

Another improvement following the New Amsterdam testing would be to develop a mechanical detail for GP injection that would be effective regardless of air handling unit capacity, configuration, or duct velocity. A higher static pressure supply fan will work well into this installation detail.

In closing, through injection into a building's traditional HVAC system, Grignard Pure's microdroplet aerosolized airborne antimicrobial was proven to be delivered effectively, reliably and consistently to all spaces served by that HVAC system at the New Amsterdam Theatre. It was demonstrated that in a microdroplet state, GP effectively behaved like a gas in its ability to distribute, dilute and disperse into occupied spaces. In real time, GP concentration in the occupied spaces was reliably measured, and feedback control loops were established to precisely control the GP production levels output from the atomizer machines.

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